Risk of Debris-Basin Failure

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Abstract: Debris basins are a common engineering structure used to control debris flows. Knowledge of the risk of failure as a function of important design variables can improve decision making and can be used as a basis for minimizing the total annual cost (i.e., construction and maintenance plus risk cost). The failure risk was computed for four policy elements: the rainfall frequency, the interval between significant watershed burn, construction and dredging accuracy, and the regularity of maintenance of the debris basin. The burn interval and the rainfall magnitude are the two most important variables associated with the failure risk, with the expected annual risk varying from less than 1% to as much as 65% for different burn intervals and rainfall frequencies. A failure to maintain the basin can double the risk or failure. The risk of failure does not appear to change much for typical construction and dredging-volume accuracy. The risk estimates were made using a model developed from data from the southern California area and the conditional expectation variance reduction technique.

Introduction

Debris flows, which are often referred to as mudflows, are movements of large soil masses through defined channel systems. They represent a significant hazard in many parts of the world. Such flows, which often consist of 50–90% solids, cause extensive damage to engineering structures such as buildings, bridges, and culverts, as well as being responsible for loss of life. In some areas, the damages from debris flows are as much as tens of millions of dollars during periods of intense rainstorms.

A debris basin is a storage structure used to contain the debris (Hollingsworth and Kovacs 1981). These basins are usually located at the mouths of steeply sloped canyons, often near the apex of an alluvial fan. Although debris flows are a continual problem, there have been very few systematic efforts made to compile data on the volumetric characteristics of debris flows (Johnson et al. 1988). Thus, accurate design methods are rarely available. Where data are available, the records are usually short and, hence, large sampling variation is expected. There is a need to consider this sampling variation in design.

Hydrometeorological variability is a primary source of the year-to-year variation in the magnitude of debris flows. Factors that are associated with hydrometeorological conditions and that affect the variability of debris-flow volumes include the rainfall volume that occurs prior to a destabilizing rainfall event, the intensity and duration of the rainfall event, the occurrence of lightning that causes extensive burning of vegetation on the watershed, and surface erosion that occurs during minor storms and is temporarily stored in

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the channel system; this interstorm surface erosion often becomes part of the interstitial mud of the debris flow. In addition to the variations caused by the hydrometeorological factors, watershed and soil characteristics are important, including the watershed slope, land cover, and both the particle-size distribution and the angle of repose of the debris material.

In designing a debris basin, the volume of storage is a primary design variable. The volume of storage required for control is directly related to both the hazard presented by the debris flow and the potential for failure of the basin. Maintenance and inspection of the basin to ensure adequate storage for control of debris flows is essential to maintain acceptable levels of failure risk. In addition to debris deposited during major storm events, eroded material continually enters the basin during minor storms; therefore, the basin must be dredged, usually on an irregular as-needed maintenance schedule. The potential for failure of the basin depends on the accuracy of both the design and the dredging. Thus, inspection of the in-place volume following construction and periodic dredging is necessary to ensure that the basin will function as intended by the designer. The risk of failure will increase if the basin volume after either construction or dredging is less than that specified in the design.

The objective of this study is to estimate the probability of failure of debris basins as a function of variables that contribute to the variations in the supply of, and demand for, basin storage. The probabilities of failure can provide useful information to both policymakers and design engineers about the optimum design. Also, an economic analysis could be based on such probabilities to evaluate the benefits and costs of alternative designs.

Risk Assessment: Mathematical Development

The performance function that expresses the relationship between the design volume of a debris basin and the volume of a debris flow can be expressed by the following equation:

$$Z = g(X_1, X_2, \ldots, X_n) \quad (1)$$

in which the X_i = design variables; with $g(\ )$ being the functional relationship between the design random variables and failure. The performance function can be defined such that the limit state, or failure surface, is given by $Z = 0$. The failure event is defined where $Z < 0$, with the survival event defined as the space where $Z > 0$. Thus, the probability of failure can be evaluated by the following integral:

$$P_f = \int\int_{Z<0} \cdots \int f_x(X_1, \ldots, X_n) dx_1 dx_2 \ldots dx_n \quad (2)$$

where f_x = joint density function of $X_1, X_2, \ldots, X_n$, and the integration is performed over the region where $Z < 0$. Because each of the design variables has a unique distribution and they can be statistically correlated, the integral of Eq. 2 cannot be easily evaluated.

A large number of methods have been developed and suggested for reliability assessment. Generally, these methods can be classified into numerically (or computationally) approximate and exact. The approximate methods are usually of the moment type, e.g., the first-order second-moment method (FOSM) and the advanced-second-moment method (ASM) (Ayyub and Haldar 1984; Ang and Tang 1984). The moment methods have limitations: on the type of probability distribution of the performance function in the case of the FOSM method, and convergence difficulty in the case of the ASM method, especially for a relatively large number of random variables in the performance function. Exact methods can be classified into two types, closed-form solution of Eq. 2 and simulation-based techniques. The efficiency of simulation methods can be largely improved by using variance-reduction techniques. A probabilistic modeling approach of Monte Carlo computer simulation with variance reduction techniques (VRT) can be used to estimate the probability of failure. Several variance-reduction techniques were used in the simulation-based estimation of probability of failure (Ayyub and Halder 1984; Ang and Tang 1984; Medchers 1987).

Conditional Expectation VRT

The performance function of a fundamental-risk assessment case is given by

$$Z = R - L \qquad (3)$$

where R = a function of the resistance or supply; and L = a function of the corresponding load effect or demand. For the case of debris-flow events, the supply is the volume of storage in the debris basin. The demand function is the volume of debris flows, i.e., the demand for storage. Therefore, the probability of failure, P_f, with failure occurring when the volume of debris flow exceeds the volume supplied in the debris basin, is given by

$$P_f = \text{Prob}(Z < 0) = \text{Prob}(R < L) \qquad (4)$$

For a randomly generated value of L (or R), say l_i (or r_i), the probability of failure is given by

$$P_{fi} = \text{Prob}(R < l_i) = F_R(l_i) \qquad (5a)$$

or

$$P_{fi} = \text{Prob}(L > r_i) = 1 - F_L(r_i) \qquad (5b)$$

where F_R and F_L = cumulative-distribution functions of R and L, respectively. Thus, for N Monte Carlo simulation cycles, the mean value of the probability of failure is given by the following equation:

$$\bar{P}_f = \left(\frac{1}{N}\sum_{i=1}^{N} P_{fi}\right) \qquad (6)$$

The variance (Var) and the coefficient of variation (C_v) of the estimated probability of failure are given by

$$\text{Var}(\bar{P}_f) = \frac{1}{N}\text{Var}(P_f) = \frac{1}{N(N-1)}\sum_{i=1}^{N}(P_{fi} - \bar{P}_f)^2 \qquad (7)$$

$$C_v(\bar{P}_f) = \frac{[\text{Var}(\bar{P}_f)]^{0.5}}{\bar{P}_f} \qquad (8)$$

The randomly generated variables of the performance function should be selected as the variables with the least variabilities, i.e., the smallest coefficients of variation. The resulting conditional expectation needs to be evaluated by some known expression of the cumulative-distribution function of the random variable that was not randomly generated.

The conditional expectation variance reduction technique reduces the variance of the simulated estimate of the probability of failure by conditioning on one of more of the generated basic random variables, such that the resulting conditional expectation can be evaluated by some known expression. Variance reduction can be achieved according to this technique by performing the following steps.

1. Using the random variable with the largest variability in a limit-state equation, i.e., the variable with the largest coefficient of variation, express and condition the variable with respect to all of the remaining random variables in the performance function.
2. Generate realizations for all of the conditional random variables except the control variable identified in step 1 using the inverse transformation method (Ang and Tang 1984; Low and Kelton 1982).
3. Calculate the conditional probability of failure for the ith simulation cycle using the cumulative-probability-distribution function of the control variable.
4. Repeat steps 2 and 3 N times, where N = integer number of simulation cycles.
5. Calculate the statistical characteristics of the resulting N conditional probabilities of failure.

The concept and the steps involved are further explained by Ayyub and Haldar (1984) and White and Ayyub (1985). According to this method, the variance of the estimated quantity is reduced by removing the variability of the control variable on which conditioning was not done. An additional advantage is that the method converges to the correct probability of failure in a relatively small number of simulation cycles.

Antithetic Variates VRT

In the method of antithetic variates, a negative correlation between different cycles of simulation is induced in order to decrease the variance of the estimated mean probability of failure. If U is a random number uniformly distributed between 0 and 1 and is used in a computer run to determine the probability of failure $P_{fi}^{(1)}$, then $(I - U)$ can be used in another run to determine the probability of failure $P_{fi}^{(2)}$. Therefore, the probability of failure at the ith simulation cycle is given by

$$P_{fi} = \frac{1}{2}\left(P_{fi}^{(1)} + P_{fi}^{(2)}\right) \quad \text{(9)}$$

Then, the mean value of the probability of failure can be calculated by Eq. 6, with the variance given by

$$\mathrm{Var}(\bar{P}_f) = \frac{1}{4N}\{\mathrm{Var}[P_{fi}^{(1)}] + \mathrm{Var}[P_{fi}^{(2)}] - 2\mathrm{Cov}[P_{fi}^{(1)}, P_{fi}^{(2)}]\} \quad \text{(10)}$$

where Cov = covariance of $P_{fi}^{(1)}$ and $P_{fi}^{(2)}$. Since the covariance of $P_{fi}^{(1)}$ and $P_{fi}^{(2)}$ is negative, the variance of P_f is expected to be reduced.

In this method, a negative correlation between different cycles of simulation is induced in order to decrease the variance of the estimated probability of failure. The method can be used with the conditional expectation VRT. The negative correlation can be achieved by using, for example, the inverse-transformation method of generating values of the random variables as defined in the previous step 2 of the conditional expectation VRT. In the random generation process for each simulation cycle, say the ith cycle, a set of random numbers based on the random variable U is used in the first stage of the ith cycle to determine the probability of failure $P_{fi}^{(1)}$. In the second stage of the ith cycle, a complementary set of random numbers based on the random variable $(I - U)$ is used to determine the probability of failure $P_{fi}^{(2)}$. Therefore, the probability of failure at the ith simulation cycle is given by Eq. 9. This results in additional reduction in the variance of the estimated probability of failure and expedites convergence. The antithetic variates VRT is described in detail by Ayyub and Haldar (1984) and White and Ayyub (1985).

Risk Assessment: Debris-Basin Failure

Factors Affecting Design Risk

Policies intended to control debris flows with debris basins should address four primary elements: The magnitude and frequency of precipitation, the frequency of watershed burn, the loss of storage in the basin due to small volumes of debris that accumulate between major debris-generating storm events, and the accuracy of excavation during construction and dredging. Debris flows most often occur when intense rainfalls follow extended periods of rainfall that saturated the steeply sloped portions of the watershed. While short-duration rainfall intensities are used as input for waterflood estimation methods, longer-duration rainfall volumes are better indicators of debris-flow potential, because they reflect both the antecedent rain and the rain that generates the debris flow. The 72 hr rainfall volume is a reasonable indicator of the combination of high-intensity debris-generating rainfall and antecedent rainfall. Debris flows can also result from snowmelt runoff (Wieczorek et al. 1985).

While the assumption of the equality of the exceedence frequency of rainfall and runoff is common in waterflood estimation, the exceedence frequency of rainfall cannot be used as the sole indicator of the frequency of the debris flow. In addition to the frequency of rainfall, the frequency of watershed-scale fires is an important element of a design policy. Fires destroy the natural vegetation, thus exposing large surface areas to the kinetic energy of the raindrops and the erosive energy of the resulting surface runoff. Furthermore, the fire sears the surface of the watershed, which reduces infiltration and increases runoff velocities. Soil moisture is retained in the soil matrix when there is little vegetation to transpire the water, thus increasing both the stress placed on the failure plane and the potential for debris slides. As the frequency of fires increases, the volume of debris flows is expected to increase. Therefore, the design model should include a variable to reflect the expected time interval between fires that destroy a significant portion of the vegetation. Design policies should specify a design burn interval. For a design policy that specifies a short burn interval, the design volume of debris will be relatively large, thus, the risk of failure will be small.

In between the major debris-producing storms, minor storms can generate significant volumes of sediment that collect in the drainage system of the watershed, as well as in the debris basin. The amount of such debris in the basin at the time of occurrence of a debris-producing storm affects the failure rate of the basin. Therefore, a debris-management policy should include a policy element that requires interstorm dredging of sediment that accumulates in debris basins. Dredging should take place just before the start of the season when most debris flows occur and when the storage taken up by interstorm sediment accumulation exceeds a certain percentage of the design volume.

Construction accuracy is the fourth factor that may influence the risk of failure of a debris basin. When the as-built volume of the basin is less than the volume specified by the designer, then the risk of failure increases. Given the value of land, there is a natural desire to minimize the area devoted to the debris basin. Thus, inspection of the debris basin to ensure that the as-built volume and the volume after dredging is at least equal to the design volume should be included as part of every debris-management policy.

Formulation of Debris Model for Risk Assessment

Given the potential importance of these four factors, a model that allows for the design uncertainty of these factors was formulated. The central part of the model is an empirical formula that relates the volume of debris flow (D_y, in cubic yards) to the 72 hr rainfall depth (P, in inches), the drainage area (A, in square miles), and the time interval between watershed burning (t, in years). Data for debris basins in the Los Angeles area were analyzed, with the following result:

$$D_y = 2{,}750P^{0.75}A^{1.25}(1 + 80e^{-0.62A-0.537t})^{0.5} \qquad (11)$$

The data base included watersheds having areas ranging from about 0.1 sq mi (0.259 km^2) to less than 3 sq mi (7.77 km^2). Only the events where at least 50% of the watershed was burned were included in the data base for calibrating Eq. 11. Where the extent of burn was less than 50%, the data did not suggest that burn significantly affected the volume of debris.

Eq. 11 is used as the base model for estimating both the supply and demand functions of Eq. 5. For the analysis of risk of debris-basin failure, the demand function reflects the variation in debris-flow volumes that result from the physical uncertainty in both precipitation and watershed burn. A drainage area of 1 sq mi (2.59 km^2) is assumed; since area was considered to be a constant in the estimation of risk, the assumption has no bearing on the assessments of failure. The precipitation was assumed to follow a log-extreme value distribution with a mean and coefficient of variation of 4.5 and 0.444, respectively. The time between forest fires was assumed to follow a log-normal distribution with a mean value and coefficient of variation of 8.0 and 1.375, respectively. The random variables P and t are assumed to be statistically uncorrelated, which is physically rational, also.

Eq. 11 is also used to compute the supply function of Eq. 3. In this case, the supply defines the design volume of storage that is available for a debris event. Thus, the base design with Eq. 11 reflects the volume required by the debris-management policy, with the policy specifying both a design precipitation depth $\bar{P}$ and a design burn interval $\bar{t}$. However, the volume computed with $\bar{P}$ and $\bar{t}$ as input to Eq. 11 should be adjusted depending on the policy specification for the maximum volume of debris that is allowed to accumulate in the basin prior to debris-producing storms before the material is dredged from the basin. An adjustment should also be made to reflect construction accuracy.

In quantifying the supply function, three design precipitation depths $\bar{P}$ are evaluated, the 2, 10, and 100 year events. Since most of the data used to calibrate Eq. 11 had burn intervals of less than 25 years, four burn intervals $\bar{t}$ are evaluated, 2, 5, 10, and 25 year intervals. The variation (or percent deviation from the design volume) in the in-place volume associated with the frequency of dredging can be represented by an exponential distribution; three policy statements are considered, with variation in the allowable interstorm accumulations of 0, 10, and 25% of the design volume. Thus, for the 10% case, for example, the interstorm debris accumulation could be 10% of the design volume before dredging would be required. As this percentage increases, of course, the supply of storage for major debris-generating storms decreases. Finally, construction accuracy was assumed to be normally distributed, and the risk was evaluated for coefficients of variations of 2 and 5%, which reflect the expected construction accuracy for cohesive and noncohesive soils, respectively. The construction accuracy was considered on the supply side of the performance function of Eq. 3 by treating the provided volume as a random variable.

Failure Assessment

A failure is defined as an event during which the demand for storage exceeds the volume supplied by the in-place design. For failure to occur, the volume of the debris flow needs to exceed the current volume of storage, where the current storage is a function of the design volume, the interstorm accumulation of sediment, and dredging accuracy. While damages are a function of the excess volume (i.e., demand minus supply), no attempt was made to assess monetary damages due to failure since a generalized economic-damage function for debris events is not available. While this definition of failure may seem simplistic because it does not distinguish between an exceedence of 1 cu yd (0.76 m^3) and 100,000 cu yd (76,000 m^3), any other definition would require site-specific information, so the results would not be of a general nature. The performance function for the purpose of failure assessment is given in the form of Eq. 3 as follows:

$$Z = V_i - \log_{10}(U)kV_D - 2{,}750P^{0.75}A^{1.25}[1 + 80e^{-0.624-0.537t}]^{0.5} \quad \text{(12)}$$

where V_i = initial provided volume; V_D = design volume; k = fraction for dredging; and U = uniform random variable (random number).

The algorithm was executed for the conditions described previously, with two levels for the construction accuracy and three policy levels each for precipitation $\bar{P}$, burn interval $\bar{t}$, and dredging of interstorm accumulation. Since dredging is a maintenance practice, rather than a principal design factor, and construction accuracy is an element of design inspection, the policy elements of the return periods of precipitation and burn are discussed separately. Fig. 1 shows the failure surface, which gives the probability of failure of a debris basin for designs based on return periods of 2–100 years for the design precipitation and 2–25 years for the design burn interval. The dashed line shows the conditions under which the failure probability equals the probability of the design rainfall. The risk of failure varies with both P

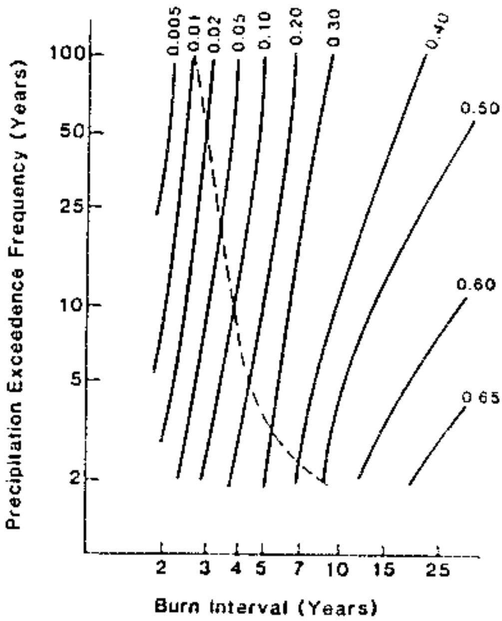

FIG. 1. Expected Annual Probabilities of Debris Basin Failure for Design Return Periods for Precipitation and Burn Interval

and t, but the variation in risk associated with P (or t) depends on the level of t (or P); thus, there is noticeable interaction between the two random variables. The risk of failure is greatest, approximately 67%, for a basin that is only designed to control the 2 year precipitation and on an infrequent burn interval of 25 years; such a design would have a very small volume of storage. When a policy specifies an infrequent burn interval, of 10 years or longer, there is a high probability of failure because, according to the watersheds used to calibrate the model of Eq. 11, burns occur more frequently than the policy specifies. The mean burn interval for the data used to calibrate Eq. 11 was 10 years; this is reflected in the failure probabilities of Fig. 1. For a more frequent burn interval $\bar{t}$ as a design input, a larger volume of storage needs to be specified in the design; therefore, the risk of failure becomes smaller. For example, for a policy based on the 2 year precipitation, the failure probability for a 2 year burn frequency will be about 8% of that for the 10 year burn interval. The risk reduction is substantially greater for policies that specify a 10 year or 100 year design precipitation. Of course, the required volume of storage, and thus the cost of design and construction, increases.

The failure probabilities specified by Fig. 1 represent average annual expected values. The 72 hr rainfall depth would have an exceedence frequency associated with it, which would be specified in the policy. The burn interval would also be a policy variable. If the rainfall frequency and burn interval are set by policy, then the design volume will control debris flows with the expected annual failure rate specified in Fig. 1. If one wanted the failure

TABLE 1. Expected Annual Failure Probabilities for Policy Burn Interval of 2 Years

Alternative dredging policies (k) (1)	Policy Exceedence Frequency of Precipitation (T) 2 year (2)	10 year (3)	100 year (4)
0.00	0.053	0.010	0.0041
0.10	0.064	0.012	0.0050
0.25	0.093	0.021	0.0083

probability for a time interval other than 1 year, then the binomial, or Poisson, risk method could be used.

For a given rainfall frequency (e.g., a 10 year event), the probability of failure increases as the burn interval increases. This is rational since, if a large burn interval is used, then Eq. 11 yields a relatively small design volume; thus, the probability that the capacity will be exceeded in any one year increases.

Debris basins must be maintained since sediment accumulates in the basins during minor, nondebris-flow storm events. If basins are not properly maintained by dredging the accumulated sediment, the storage specified by the design engineer will not be available during a debris-producing storm event. Thus, the probability of failure is expected to increase as the time interval between dredging increases. Three policy conditions were evaluated, each representing a different fraction of the basin storage that was permitted to be occupied by sediment accumulation prior to dredging. Specifically, fractions of 0, 0.1, and 0.25 were considered, with a fraction (k) of 0 indicating a policy that requires that all the sediment or debris be dredged immediately after it has been deposited. This may be considered impractical since it would require continuous monitoring. Thus, the other levels studied reflect varying levels of practicality and the availability of public funds for maintenance.

The risk of failure increases as the fraction of deposition permitted increases. For policies based on long burn intervals, 10 years or more, the failure probability showed little change with a change in the value of k; for these cases, the failure probability was controlled by the burn interval. However, for a policy that specifies a burn interval of 2 years, the value of k has a more substantial effect on the failure probability. Table 1 shows the effect. For a policy that allows as much as 25% of the basin volume to be taken up by sediment deposition from minor storms, the risk of failure is about two times the risk where continual maintenance is provided. This risk is sufficient to warrant recognition of the need for all policies to provide for both maintenance between debris-generating storms and monitoring of sediment accumulation during these periods. The policy should specify a value of k that is reasonable from the standpoint of the availability of maintenance resources and the cost associated with the risk of failure.

The fourth factor included in the model was the construction and dredging accuracy. This was assumed to be normally distributed, which reflects the possibility that the basin may have either a larger or smaller constructed volume than that specified in the design. A larger in-place volume would reduce the risk of failure. The resulting estimates of failure risk indicate that the construction accuracy has little effect on the overall risk of failure, with a maximum variation of about 3%. Thus, design risk is relatively insensitive to construction accuracy as long as the construction practice, including inspection, assures that the volume is within 5% of the design volume.

Conclusions and Analysis

Debris basins are a recognized alternative for controlling debris flows. The central element of design is the volume of storage. The size of a debris basin can be designed by balancing construction, operation, and maintenance costs with the benefits provided through the prevention of debris flows from damaging downstream public facilities and causing the loss of life. Best use of public resources will be made if the policies on which basin designs are chosen account for the primary factors that cause debris-basin failure. Safer designs should result when design practices account for the risk of failure.

The risk of debris-basin failure associated with four controlling factors was studied. The return period of the rainfall represents the effects of hydrometeorological characteristics on debris generation. The time interval between substantial burns on watersheds reflects the condition of the land cover. The size of an in-place debris basin is affected by construction and inspection practices, so the accuracy of the in-place volume with respect to the design volume is used as a variable for risk assessment. Maintenance of debris basins is costly, yet an important determinant of the failure risk of a debris basin; the design volume of a debris basin must be maintained by dredging the sediment that accumulates during minor storm events that occur between debris-generating storms. Policies should reflect the risk of failure due to these four factors, each of which is a random variable that must be addressed in the formulation of debris-management policies.

An evaluation of the risk of failure of debris was made using the conditional expectation variance reduction technique, with a debris-flow model developed from data for the southern California area. The burn interval is a major factor in establishing the risk of failure. The results suggest that when the expected burn interval is shorter than the average interval, which was 10 years for the data evaluated, the risk of failure can increase substantially. For a design policy based on a 100 year return period rainfall, the risk of failure can increase by a factor of 20 when a long burn interval is used. Depending on the damages associated with failure, it appears that it is reasonable for a policy to use a short burn interval, possibly on the order of 2–5 years. Specifying a longer burn interval will substantially increase the risk of failure.

Rainfall is also a primary factor in generating debris flows, and the volume of debris varies with the exceedence frequency of the storm. If the design is based on a small rainfall volume, the design capacity of the debris basin will not be adequate to control the larger debris flows, and the risk of failure will increase substantially. The failure probabilities reported herein suggest that policies should use return periods of at least 10 years for the precipitation in order to achieve a reasonable level of risk.

It is common in waterflood policies to use a design method that assumes that the frequency of the peak discharge rate equals the exceedence frequency of the precipitation. The risk-of-failure surface of Fig. 1 indicates that this is a poor assumption in debris-flow modeling. The dashed line on

Fig. 1 represents the condition where the probability of debris-basin failure equals the probability of the precipitation. Based on this line, a design burn interval $\bar{i}$ of 2 or 3 years appears most appropriate for debris-management policies. Such a criterion would ensure that the risk of failure is smaller than the exceedence frequency of the design precipitation.

The risk of failure increases substantially when the debris basin is not maintained. Sediment that accumulates in the basin from the minor storms that occur between major debris-generating storms must be dredged. The design volume of a debris basin should reflect the maintenance policy of the locality. If maintenance capabilities are limited, design volumes should be increased to allow for the storage that is necessary to control debris flows that occur in a basin in which sediment has accumulated since the most recent dredging. It appears that the risk of failure will not increase substantially if a maintenance policy allows for an accumulation of 5% to a maximum of 10% of the storage volume. The loss of storage due to interstorm-sediment accumulation can substantially increase the risk of failure when more than 5–10% of the design storage volume is not available for debris flow. Where resources for maintenance are scarce, it may be better to increase the design capacity by 10–20% so that the risk of failure will not increase unreasonably.

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